THE USE OF CLIMATE MODELS IN FORECASTING FUTURE CLIMATE CHANGE

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ABSTRACT

For more than 25 years, climate models have been used to investigate the impact of greehouse gases on the earth's climate. These models, which have become increasingly comprehensive, have provided much of the scientific evidence regarding the potential changes in climate due to anthropogenic increases in greehouse gases. Recently, the advent of more realistic models of the coupled atmosphere-ocean system have made it possible to simulate the response of climate to gradually increasing greehouse gases. Is it appropriate to regard the output from such models as forecasts of future climate change? The answer depends on a careful analysis of the mechanisms affecting climate and the ability to incorporate them faithfully in climate models.

DESIGN OF CLIMATE MODEL EXPERIMENTS

Climate models have been used to investigate the impact of greenhouse gases on the earth's climate for more than 25 years. The state of the art has progressed dramatically during this period, from relatively simple one-dimensional models of radiative-convective equilibrium to three-dimenional models of the coupled atmosphere-ocean system. The development of a hierarchy of climate models for the study of climate change due to anthropogenic increases in greenhouse gases has led to a variety of research studies. Most of these can be separated into three categories based on their experimental design. Using terminology taken from the recent Intergovernmental Panel on Climate Change (IPCC) Scientific Assessment (Houghton et al.[1]), these are equilibrium response studies, transient response studies, and time-dependent response studies. Experiments in the last category will be the primary subject of this paper.

Time-dependent response studies use models of the coupled atmosphere-ocean system to simulate a change in climate in response to gradually increasing greenhouse gas concentrations. Such gradually increasing concentrations are similar to what is occurring in the real climate system. A number of time-dependent response studies have been performed, primarily using general circulation models of the atmosphere coupled with dynamical ocean models. An important result from these studies has been the identification of important regional variations in the rate of warming due to increasing greenhouse gases. In addition, these studies have allowed estimates to be made of the rate of warming in response to an increase in greenhouse gas concentrations with a rate similar to that occurring presently. But can these estimates be regarded as forecasts of climate change? To answer this question, it is necessary to consider the mechanisms influencing climate and the ability to represent them faithfully in climate models.

FACTORS INFLUENCING CLIMATE

A variety of external factors can be important on the time scales relevant to anthropogenic climate change (i.e., years to decades). These include atmospheric greenhouse gas concentrations, volcanic aerosols, variations in solar radiation, and anthropogenic sulfate aerosols. In addition, internal variability inherent to the climate system may produce variations in climate comparable in magnitude to some of the externally forced variations.

A number of greenhouse gases have been increasing in concentration since the pre-industrial era as a result of human activities. These gases, which include carbon dioxide, chloroflourocarbons, methane, and nitrous oxide, produce a tropospheric heating effect by increasing the infrared opacity of the atmosphere. The increases of all of these gases provide an enhancement of the heating associated with the natural greenhouse effect.

Large volcanic eruptions can inject sulfur dioxide gas into the stratosphere, forming sulfuric acid aerosols that can scatter incoming solar radiation, increase planetary albedo, and thus have a significant impact on the earth's radiation balance. The combination of a reduction of total solar radiation with the warming due to the thermal infrared effects of the aerosols results in a small net cooling effect at the earth's surface, which can persist for 1 or 2 years following an eruption.

Variations in solar radiation are capable of producing changes in changes in climate. Changes in the latitudinal and seasonal distribution of insolation associated with periodic variations in the earth's orbital parameters are believed to be responsible for the glacial-interglacial cycles of the Quaternary era. These orbital variations have time scales of 10^4 to 10^5 years. Much less is known about changes in insolation on shorter time scales (10 to 10^3 years), since precise monitoring of solar irradiance has existed for little more than a decade. However, some evidence has been offered for irradiance variations of up to 0.5 percent on these time scales.

Anthropogenic sulfur emissions may also have potential climatic effects through two mechansims. A direct effect is the scattering of incoming solar radiation by sulfate aerosols. However, this effect may not necessarily result in an increase of planetary albedo, depending on other factors such as the albedo of the underlying surface and the solar elevation angle. An indirect effect is the potential of aerosol particles to increase cloud albedo by acting as cloud condensation nuclei. Both of these effects are extremely difficult to assess quantitatively, although recent work suggests a net cooling effect at the surface.

In addition to variations in climate resulting from these external forcing factors, substantial variability appears to occur in the climate system even in the absence of external forcing, spanning a wide range of time scales. Much of this variability involves interactions between the atmospheric and oceanic components of the climate system. The well-known El Nino- Southern Oscillation phenomenon is an example, with climatic effects in widespread areas around the globe. More recently, models of the coupled ocean-atmosphere system have displayed variability of oceanic overturning (with accompanying atmospheric variations) on interdecadal time scales. On shorter time scales, climate model experiments have demonstrated that substantial variability can occur even without changes in the ocean. Interactions with the land surface and internal atmospheric dynamics are likely sources of this variability.

REPRESENTATION IN CLIMATE MODELS

The extent to which these external forcing factors can be incorporated in climate model calculations is crucial in determining whether model output can be used as forecasts of future climate change. Two conditions must be met for each to be successfully incorporated. First, we need to know how to model the physical effect of that factor. Second, we need to know how that factor varies in time. For hindcasts (i. e., attempts to reproduce the variations in climate up to the present) only past variations in forcing need be known; for forecasts, both past and future variations are necessary. In this section, the state of our current ability to represent the external forcing factors in hindcasts and forecasts will be examined.

Greenhouse gases seem by far to be the external forcing factor most readily represented in a climate hindcast. The development of more accurate radiative transfer models has enabled reasonable estimates of the radiative effects of the various greenhouse gases as a function of their atmospheric concentration. Despite some uncertainties in the basic spectroscopic data for many gases (particularly the chloroflourocarbons) and differences among the radiative transfer models, the radiative effects of greenhouse gases is a relatively mature and well-understood component of the climate modeling problem. Evidence of past increases in concentration of the various greenhouse gases are readily available from two sources. In recent decades, direct measurements have been taken at locations relatively free of local contamination (e. g., CO_2 at Mauna Loa). Records from earlier times have been extracted from ice cores in Greenland and Antarctica. As snow is transformed into glacial ice, air becomes trapped as bubbles in the ice. These bubbles contain fossil air, which can be dated based on ice accumulation rates.

Representing the past history of the other forcing factors is much more problematic. In principle it should be relatively straightforward to model the effect of volcanic aerosols in the stratosphere, although in practice it can be difficult do so quantitatively. Measurements have only been available in recent years. Historical records provide clues to earlier eruptions, although it can be quite difficult to reconstruct the sulfur content of the erupted material and whether or not it reaches the stratosphere. This is important, since the sulfate aerosol particles have much longer lifetimes in the stratosphere than in the troposphere. Increased acidity in glacial ice cores has also been linked to sulfate aerosol-producing eruptions, but again there are difficulties in interpreting these proxy data. Thus reconstructions of past volcanic activity often differ from each other.

For changes in solar irradiance, the difficulty is in documenting past changes in this quantity based on the short period of precise observations. These have indicated that irradiance varies in conjunction with the 11-year cycle of solar magnetic activity (i. e., the sunspot cycle), with a total variation of approximately 0.1 percent. There has been speculation that variations in solar output may occur on longer timescales. Proxies of solar magnetic acitivity, such as sunspot numbers, carbon-14, and beryllium-10, indicate substantial variations on time scales of decades to centuries. Observations of solar radius also show variations on these time scales. There has been some suggestion that these changes may be correlated with solar irradiance, with variations of as large as 0.5 percent. Substantial work is underway to explore possible mechanisms for such variations, including physically-based modeling and astronomical studies of Sun-like stars. But at this time, little evidence exists to quantify them.

The radiative properties of tropospheric sulfate aerosols resulting from industrial activity contribute to substantial difficulty in representing them in climate model hindcasts. Large uncertainties exists in both their direct and indirect effects. Because of their relatively short lifetimes in the troposphere (days to weeks), the distribution of sulfate aerosols is not as uniform in space and time as those of the greenhouse gases, since their sources are confined to the continents, particularly the densely populated and industrialized areas. This adds another complication to including their effects in climate model calculations, even though there are some estimates of the history of sulfur emissions which could be used in chemistry/transport models to estimate aerosol concentrations.

Many of the problems in representing the effects of these external forcing factors are exacerbated when forecasting future climate. Future changes in greenhouse gas concentrations depend on the emission rates of the gases and biogeochemical processes operating in the atmosphere-ocean system. Since future emission rates will be affected by economic conditions, technology, and public policy, substantial uncertainty exists as to their magnitude. To account for this, the IPCC used a variety of scenarios of future greenhouse gas concentrations, yielding a range of time-dependent climate change estimates. This method may be the only reasonable way to quantify the uncertainty inherent in estimates of future greenhouse gas concentrations. Projecting future concentrations of anthropogenic sulfate aerosols involves similar difficulties, including the added complication that their spatial patterns can be affected by changes in the geographical distribution of sulfur emissions.

Estimating future variations in solar radiation would probably require such a reconstruction of past variations along with evidence of a periodic nature that can be extrapolated forward in time. Until the causes of solar variability are better understood and the variations in solar output are better quantified, this remains a daunting problem. The obvious difficulty of forecasting future volcanic eruptions makes it impossible to include this effect in climate change projections more than a year or two in length. Fortunately, the climatic effects of an individual eruption are felt for no more than a few years, so only a period of frequent large eruptions would influence temperature on decadal time scales.

In making forecasts (or hindcasts) of climate change, the internal variability inherent in the climate system can be an additional complicating factor. While the coupled atmosphere-ocean climate models used for time-dependent response studies have shown an ability to simulate such variability in the frequency domain, there is no reason why the time variations in climate associated with this variability should by synchronous with those in the real climate system. While deterministic predictions of some of this variability may be possible given accurate specification of initial conditions in the atmosphere and ocean (as evidenced by reports of skillful forecasts of the El Nino phenomenon), further research is required to explore this possibility. For the time being, the manifestations of internal variability must of necessity be regarded as climatic "noise" that can obscure the climate variations associated with external forcing factors.

ARE CLIMATE MODEL SIMULATIONS FORECASTS?

In the time-dependent response studies that have been conducted to date, the impact of increasing greenhouse gases typically has been the only external forcing included. The time-dependence of this forcing (i. e., the time series of greenhouse gas concentations) has generally been idealized. In some experiments, the CO_2 concentration (taken as a surrogate for all greenhouse gases) has been increased at an annual rate approximately equivalent to the current rate of increase. In others, a range of future growth rates for atmospheric greenhouse gas concentrations have been used to yield a series of future climate change scenarios, in an effort to explicitly incorporate some of the uncertainty associated with future emission rates.

Representing only the greenhouse gas forcing (and doing so in an idealized manner) may have a number of interesting consequences for the interpretation of these experiments. The idealized time-dependent greenhouse gas forcing differs from that actually observed. Thus quantitative comparisons of simulated and observed temperature changes may be of limited value. This is of particular concern given the possibility that changes in the other external forcing factors, along with internal variability, may also have influenced global temperature during this period. Since the increase in greenhouse gas forcing has been relatively small until the past few decades and the ocean should delay the response of the climate system, the effect of this forcing over the historical record may be comparable in magnitude to those associated with other factors. Thus there is no reason to expect quantitative agreement between the simulated and observed evolution of global temperature during this period.

For estimates of future climate change, these difficulties could become somewhat better resolved. For the range of emission scenarios considered by IPCC, the greenhouse gas forcing is expected to grow well beyond the plausible contributions of volcanic aerosols and solar variability during the next century. Thus the greenhouse gas effect would be expected to become dominant over that time, such that an estimate of its magnitude could be a good approximation of a climate change forecast. However, the effect of anthropogenic sulfate aerosols is a complicating factor. Because the sulfate forcing has been hypothesized to have the opposite sign and could also increase as a result of economic growth, some fraction of the greenhouse gas effect may be counteracted as a result.

Thus to increase the ability to make climate forecasts on time scales from decades to centuries, it seems important that the anthropogenic sulfate effect be better quantified. Much work also needs to be done on the effects of volcanic aerosols, solar radiation variations, and internal variability of the atmosphere-ocean system. Concurrently, progress in climate modeling is also necessary to narrow the range of uncertainty regarding climate feedback mechanisms that can amplify or reduce the direct effects of external forcing. Better observations of oceanic variations and processes may prove useful in understanding the role of the oceans. In the meantime, caution is required when interpreting the results from climate modeling experiments.

ACKNOWLEDGMENTS

The efforts of Working Group 1 of the Intergovernmental Panel on Climate Change[1] in compiling a comprehensive review of research reagrding this topic have been very helpful to me. I recommend their book as a starting point for those interested in this issue as it contains references for much of the information used in preparing this paper. I also thank S. Manabe and R. J. Stouffer for their comments.

REFERENCES

(1)Houghton, J. T.; Jenkins, G. J.; Ephraums, J. J.; eds. Climate Change: The IPCC Scientific Assessment, cambridge University Press, 1990, 365 pp.

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